Methods for reducing singly reflected rays on the Wolter-I focusing figures of the FOXSI rocket experiment

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ABSTRACT

In high energy solar astrophysics, imaging hard X-rays by direct focusing offers higher dynamic range and greater sensitivity compared to past techniques that used indirect imaging. The Focusing Optics X-ray Solar Imager (FOXSI) is a sounding rocket payload which uses seven sets of nested Wolter-I figured mirrors that, together with seven high-sensitivity semiconductor detectors, observes the Sun in hard X-rays by direct focusing. The FOXSI rocket has successfully flown twice and is funded to fly a third time in Summer 2018.

The Wolter-I geometry consists of two consecutive mirrors, one paraboloid, and one hyperboloid, that reflect photons at grazing angles. Correctly focused X-rays reflect twice, once per mirror segment. For extended sources, like the Sun, off-axis photons at certain incident angles can reflect on only one mirror and still reach the focal plane, generating a pattern of single-bounce photons that can limit the sensitivity of the observation of faint focused X-rays. Understanding and cutting down the singly reflected rays on the FOXSI optics will maximize the instrument's sensitivity of the faintest solar sources for future flights. We present an analysis of the FOXSI singly reflected rays based on ray-tracing simulations, as well as the effectiveness of different physical strategies to reduce them.

Keywords: FOXSI, X-ray telescope, singly reflected rays analysis, Wolter-I optics

1. INTRODUCTION

The Focusing Optics X-ray Solar Imager (FOXSI) is a sounding rocket payload that has flown twice as part of the Low Cost Access to Space (LCAS) program of NASA.[1,2] It is funded for a third flight scheduled for Summer 2018. FOXSI uses Wolter-I type mirrors together with semiconductor strip detectors to observe 5-20 keV solar X-rays. The FOXSI optics consists of a set of concentrically nested multi-shell Wolter-I figures. Each figure contains two mirrors, a paraboloid primary and a hyperboloid secondary, that together redirect grazing angle incidence X-rays towards the focal plane. For the first flight, FOXSI had a total of seven nested Wolter-I figures within each of the seven optical modules. For the second flight, two of the optical modules were upgraded to 10-shell sets. Two modules will be upgraded for the third flight such that there will be a total of four 10-shells, and three 7-shells optical modules.

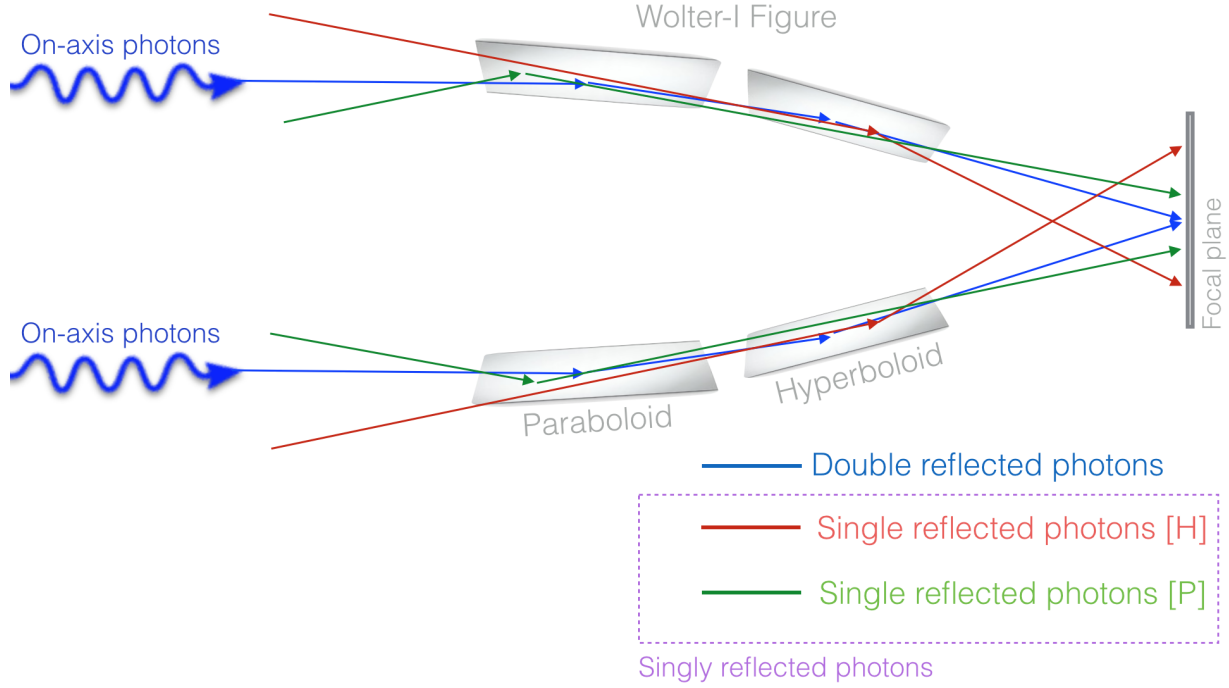Further author information:
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Figure 1. Cartoon showing the cross-section for one of the Wolter-I figures going at the front of the FOXSI rocket payload. Singly reflected rays (green and red lines) create a pattern which net effect is to decrease the SNR at the focal plane. By reducing the singly reflected rays pattern, the sensitivity of the optics is substantially improved.

Due to the spacing between shells of the FOXSI optics, not all X-rays that reach the focal plane come from the FOXSI field of view by a double reflection. Legitimate X-rays entering the telescope aperture must reflect twice, a reflection onto the primary followed by a reflection onto the secondary segment of a shell. For FOXSI, some X-rays, here referred to as *singly reflected rays*, can still reach the focal plane in two different configurations: i) by having a single reflection onto the paraboloid primary. ii) by having a single reflection onto the hyperboloid secondary. Reducing, or completely eliminating, single reflected rays is a desirable quality for improving the general performance of any Wolter-I type X-rays telescope. Particularly, by blocking most of the non-focused X-rays, we will maximize the sensitivity of FOXSI for future flights.

We evaluated several methods of reducing singly reflected rays by including an extra optical component at the front of the FOXSI telescopes. Ideas included an ensemble of nested cylindrical baffles, two sets of flat blades perpendicular to each other, a honeycomb collimator structure, and an angular slice blocker. We discuss each of the options above, and show the last two as reliable techniques we will use for upcoming flights of the FOXSI sounding rocket and possible future satellite missions.

2. SINGLY REFLECTED RAYS

Singly reflected rays patterns on the focal plane of Wolter-I type X-rays telescopes due to off-axis sources is a rather well know problem for this sort of direct focusing optics.[3–5] As illustrated in figure 1, this contamination is produced when X-rays reach the focal plane by reflecting only once on either the primary or the secondary segment of one of the Wolter-I shells.

Understanding the singly reflected rays pattern, and its geometric origin on a Wolter-I figure, is crucial to design an optical device able to reduce the total amount of singly reflected rays reaching the FOXSI detectors. We addressed this problem in two directions. i) By running ray tracing simulations with the parameters for off-axis sources placed in front of a FOXSI-like optical module. 2) By measuring the actual point spread function
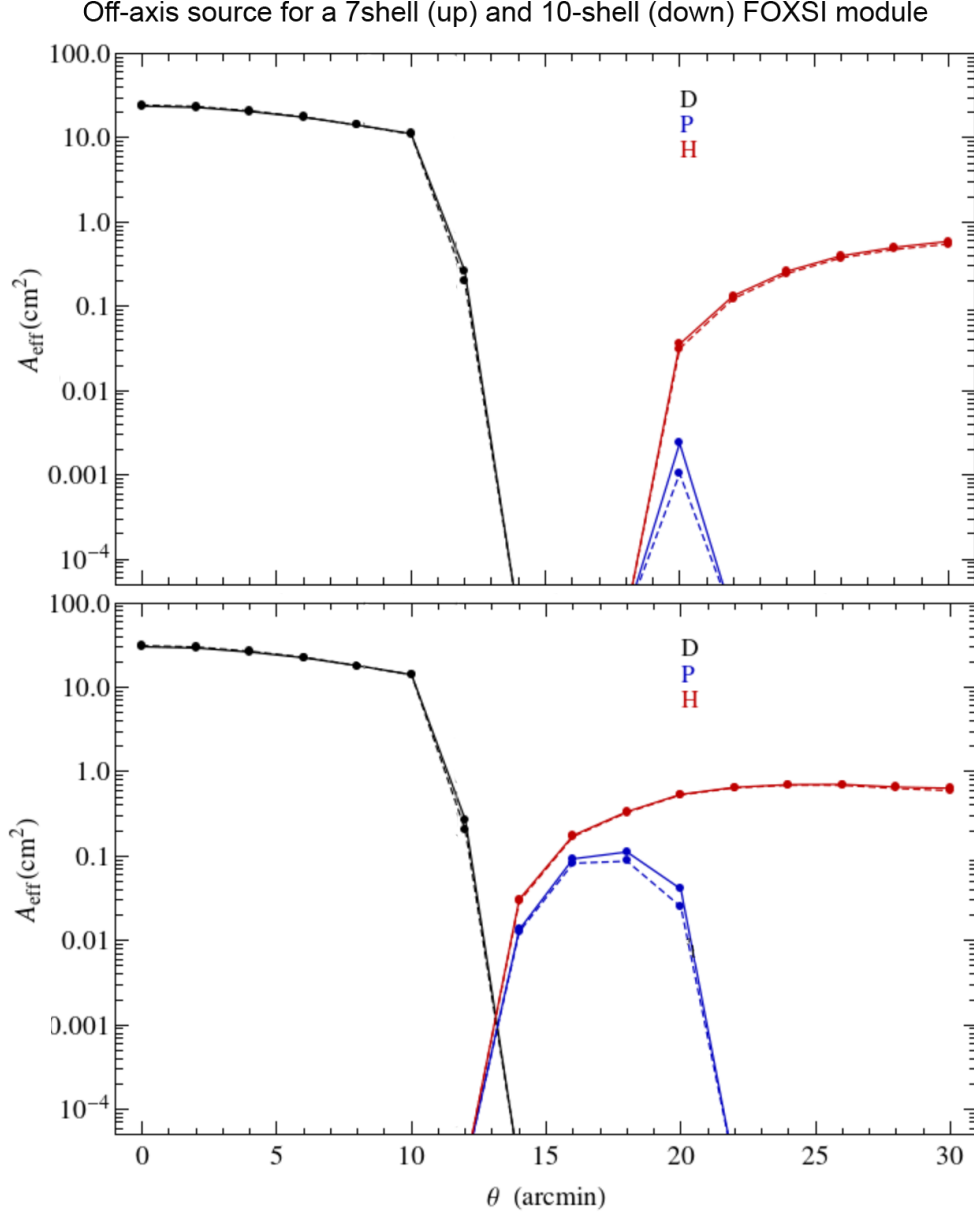
Figure 2. Effective areas for a 7-shell (up) and a 10-shell (down) FOXSI optical module, $A_{eff}(\theta)$ in cm^2, at 5 keV (solid lines) and 8 keV (dashed lines), vs. off-axis angle, θ. In arcmin. In black doubly reflected rays (D), in blue and red singly reflected rays by the paraboloid (P) and hyperboloid (H) mirror segment respectively.

(PSF) of one of the 7-shell FOXSI modules, set at different off-axis configurations, using the 100-meters Stray Light Facility at the NASA *Marshall Space Flight Center* (NMSFC).

2.1 FOXSI optics ray tracing simulations

The performance of the FOXSI optics was assessed by using Monte Carlo ray trace simulation written in Mathematica. Ronald F. Elsnera et.al.[6] describe the method used in that simulation. In general, that method includes extra polynomial terms that for a Wolter-I prescription are not necessary and then set to zero.

Figure 2 displays effective areas, $A_{eff}(\theta)$ in cm^2, vs. off-axis angle, θ, in arcmin, for a single telescope module
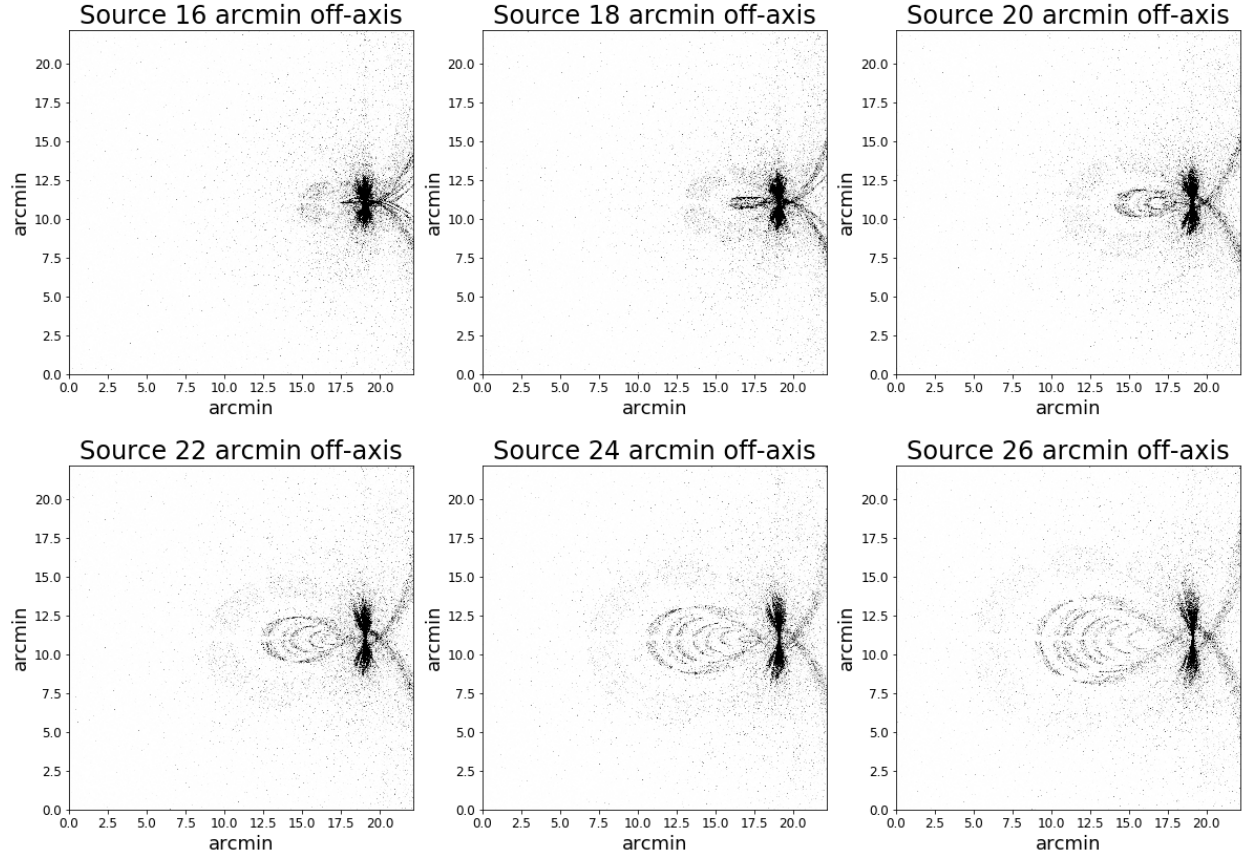
Figure 3. Point Spread Function for a real 7-shell FOXSI optical module for a X-ray source located at off-axis angles ranging from 16 to 26 arcmin. The experiment was performed at the 100-meters Stray Light Facility at the NMSFC.

with 7 (up) and 10 (down) shells, ideal mirror surfaces, for 5 keV (solid lines) and 8 keV (dashed lines), and with the detector at the nominal focal plane. Reflectivities at each point where a ray intersects a mirror surface are calculated assuming 100 Å of 90% bulk density Iridium on a semi-infinite layer of 100% bulk density Nickel, using atomic scattering factors taken from the Lawrence Berkeley Laboratorys Center for X-Ray Optics website[*]. Doubly (D) reflected rays are shown in black, rays singly reflected from paraboloid (P) segments in blue, and rays singly reflected from hyperboloid (H) segments in red. In the cases of P and H singles, and the angle θ denotes the source location.

From figure 2 we observe that for both, 7 and 10-shell modules, singly reflected rays come mostly from the hyperboloid segments. Also, that for a 7-shell telescope only sources at off-axis angles greater than 18 arcmin can contaminate the focal plane with singly reflected rays, while for a 10-shell optics that limit is lower, set in between 12 and 13 arcmin. These limits are crucial for designing methods to decrease the singly reflected rays pattern, since they constrain the physical dimensions and parameters of the collimators.

2.2 Effect of singly reflected rays on the PSF for off-axis sources

We set one of the 7-shell FOXSI optics inside the X-rays path of the 100-meters Stray Light Facility at the NMSFC. Using a *Large Area Imaging CCD Detector - iKon-L 936*[†] we measured the PSF for different off-axis configurations of the X-ray beam. Figure 3 the PSF for off-axis angles from 14 up to 26 arcmin in steps of 2 arcmin. These PSFs spread out covering angles close to 30 arcmin, deteriorating the overall quality of the images.

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[*]http://henke.lbl.gov/optical_constants/

[†]http://www.azom.com/equipment-details.aspx?EquipID=393

The most dispersed features of the patterns correspond to singly reflected rays. Finding a method to reduce singly reflected rays will appreciably the sensitivity and dynamic range of the FOXSI optics. The complexity of the PSF for off-xis sources, and its high dependance on the morphology and location of the sources, make difficult a post-flight cleaning process of the images. Instead, we decided to study a way to include an extra hardware element able to limit the pass of singly reflected rays to focal plane.

3. METHODS TO REDUCE SINGLY REFLECTED RAYS

The design of the piece of hardware needed to reduce singly reflected rays is constrained to the room and weight available inside the FOXSI sounding rocket payload. Thus, any extra component we plan to attach to the front of the FOXSI telescopes need to be shorter than 30 cm and lighter than 2kg. Also, the shape of such components must not interfere with the components used to identify and point to the Sun during the flight.

We considered three different methods of reducing singly reflected X-rays that can be summarized in three categories: i) Cylindric baffles. ii) Honeycomb-type collimators. iii) Angular slice blocker. Below we discuss the characteristics for each hardware element, and the effectiveness at stopping singly reflected rays form off-axis sources.

3.0.1 Cylindrical baffles

This concept consists of concentric cylindrical shaped baffles, 12-inches long, suitable to be placed in front of "ideally" every Wolter-I figure of a FOXSI optical module. Figure 4 shows that mirrors with a small radius contribute the most to the singly reflected rays pattern than those most external mirrors in an optical module. Attaching baffles to at least the five inner mirrors of a ten-shell module would substantially reduce the single bounce photons impinging the focal plane.
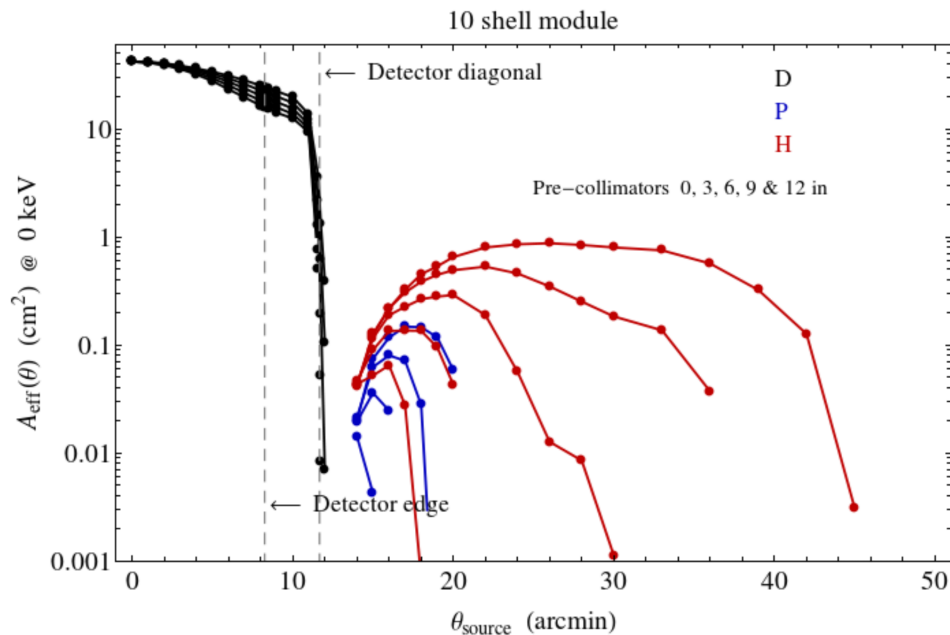

Figure 4. Effective area obtained from the ray trace simulation for a 10-shell FOXSI module. In black the effective area for the double reflected rays. Lines blue and red represent the effective area for singly reflected rays from the paraboloid and hyperboloid segment respectively. It can be observed that the flux of singly reflected rays decrease by increasing the baffles lengths.

These baffles can be fabricated by using the same electrodeposition technique implemented for moulding the FOXSI Wolter-I mirrors.[1] The baffles would have a low X-ray reflection efficiency that can be obtained by no polishing the mandrels used for the production of the baffles.

The biggest advantage of this technique is that the baffles would be light and would have precise cylindrical shapes. The major problem is that this solution is not so efficient at blocking singly reflected rays as evidenced from figure 4. Also, this method requieres long baffles, which makes it less attractive for satellites that use Wolter-I figures.

3.1 Honeycomb type collimators

The low effectiveness of the baffles at reducing singly reflected rays is mainly due to the big gaps that exist in between consecutive Wolter-I figures. One way to counter for that is by using honeycomb-type collimators filling those gaps. We explored three different technologies to implement honeycomb-type collimator at the front of the FOXSI optics. They are: i) Titanium 3D printed collimator. ii) Optical fibers for X-rays. iii) Perpendicular blades.
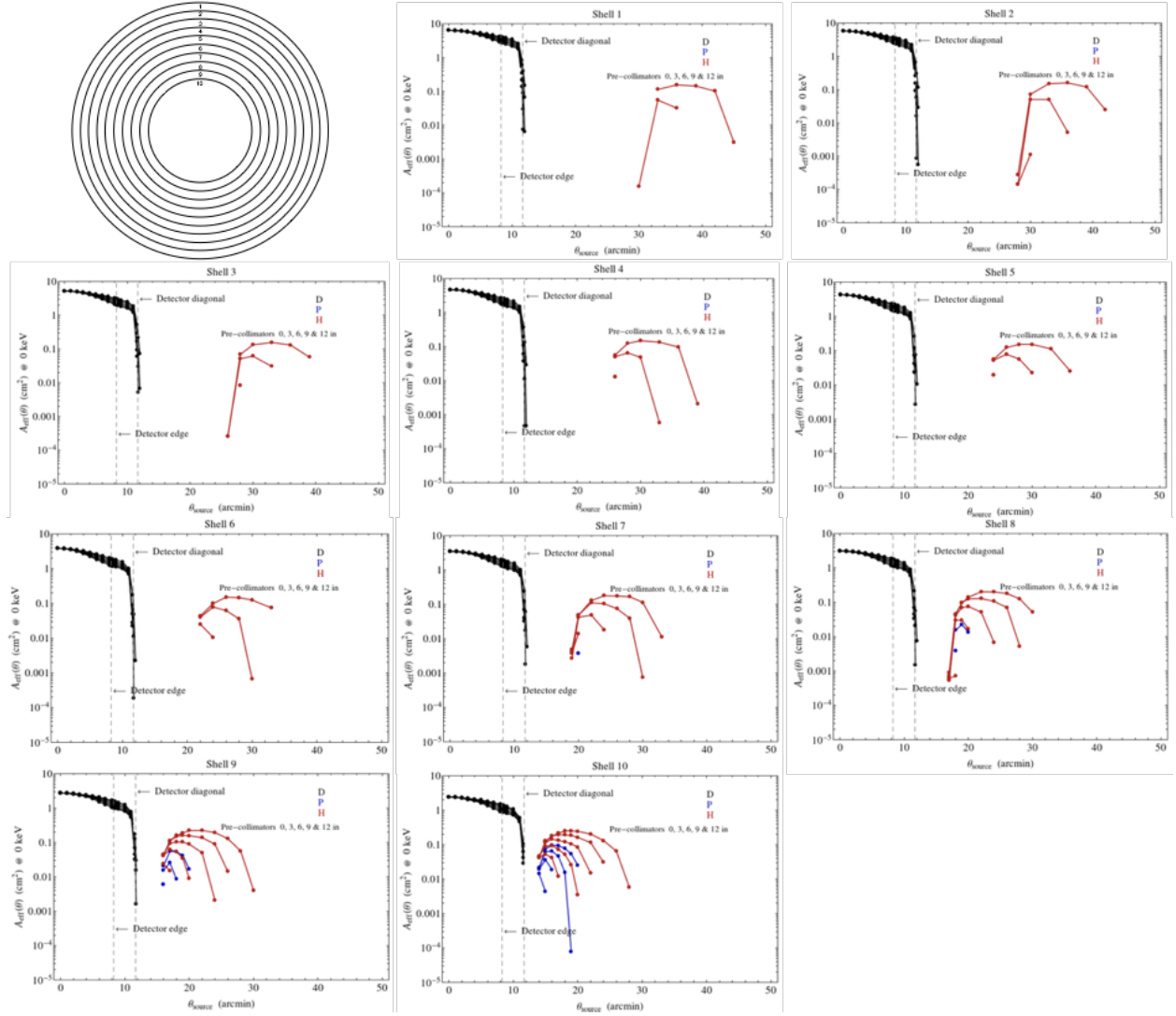

Figure 5. Sinfly reflected rays for each of the shells that shape the FOXSI telescopes.

3.1.1 Titanium 3D printed honeycomb collimator

The 3D printed collimators were designed by us and made by the Japanese company $TORAY$[‡] The thinest wall thickness this company offers is 120 microns for 1mm diameter holes. These dimensions requiere a 25 cm long collimator to block off-axis singly reflected rays coming from angles greater than 18 arcmin.
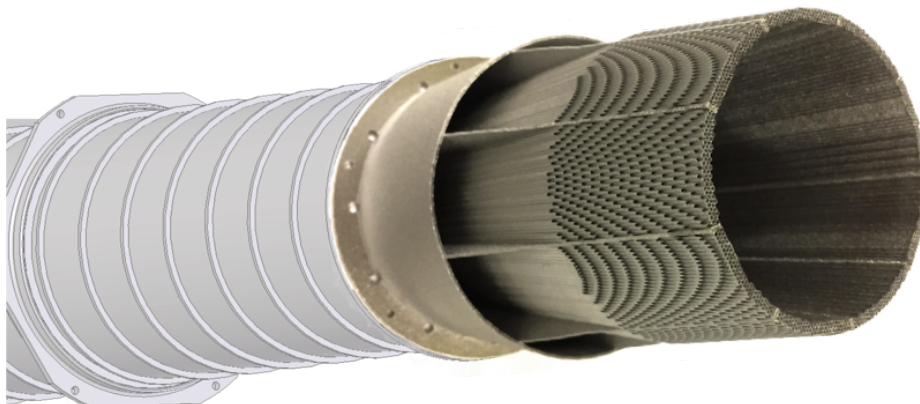

Figure 6. Picture of the one of the Titanium 3D printed collimator.

Results from the ray trace simulation showed that most of the off-axis singly reflected rays come from the inner mirrors in a FOXSI telescope, see figure 5. To minimize the weight we designed a collimator with a honeycomb structure only in front of the four most inner mirrors for a 7 shell optics. Additionally, we implemented a stratified length for the collimator height considering the smallest off-axis angle for which singly reflected rays are not negligible on each shell. The final version of the 3D printed collimator has a maximum height of 19.5cm, a mass of 0.8kg, and a nominal geometrical open area for an at infinity on axis source of 75%. We compared the effective area for one the FOXSI optical modules with and without collimator at the 100-meter Stray Light Facility (SLF) at the NMSFC. We found the effective area of one of the 7-shell modules is decreased by a $\sim 40\%$ by having the 3D collimator set at the front when the X-ray generator is aligned with optics axis. We believed this discrepancy between the geometrical nominal open area of the 3D printed collimator and the reduction of the effective area at the 100-meters SLF is mainly due to have the X-ray generator at a finite distance. Further exploration in this direction is needed.

The 3D printed collimator was design in only one piece with an interfase that perfectly sits in the front of the spider that holds the shells of a FOXSI optical module. Figure 6 shows a picture of one of the 3D printed collimator completely terminated and how it sits in front of one of the FOXSI telescopes.

3.1.2 Optical fibers for X-rays as honeycomb collimator for FOXSI

This solution consists on modify the geometry and internal reflectivity of a large set of poly-capillaries originally designed to collect X-rays from an X-ray source and focus them to a small spot. Common applications of polycapillary focusing optics lay on the X-ray fluorescence analysis of samples like circuit board, alloys, and metals.

The X-ray Optical Systems (XOS) is a company located in Albany New York which fabricates and distributes this kind of polycapillaries for X-rays with energies ranging from 50 eV up to 50 keV. XOS offers the possibility of customize the polycapillaries for different geometries including a design of straight and parallel hexagonal capillaries, matching the honeycomb structure needed for the FOXSI collimators. Using the smallest possible wall thickness XOS can achieve (15μm) to maintain a 80% open area on-axis, a 0.15 mm hole diameter single capillary is required. XOS can fabricate a bundle of capillaries forming a one-piece cylindrical shaped structure with a maximum radius of ~ 2 cm. To cover all the front of one of the FOXSI telescopes, i.e. a circular cross-section of 5.5 cm radius, several tens of polycapillary bundles need to be glue together. The current design

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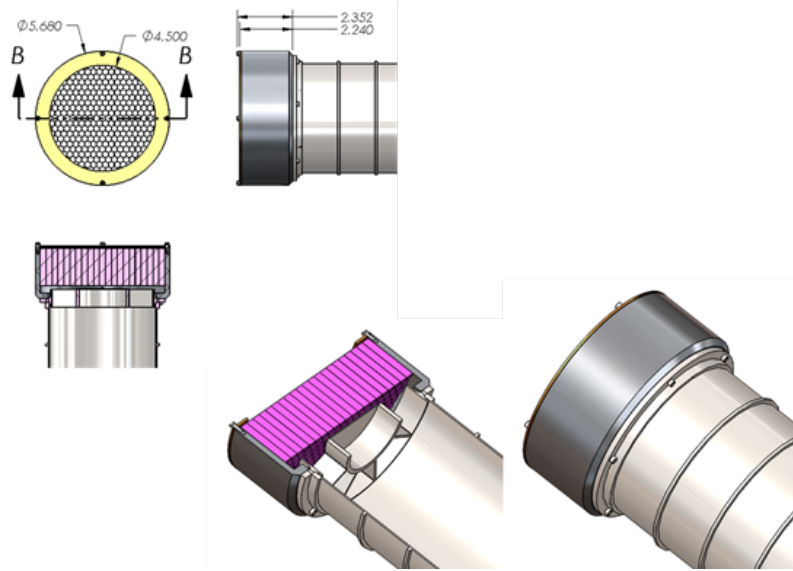[‡]http://www.toray.com/products/plastics/pla_0060.html

Figure 7. XOS polycapillaries. Mechanical design of attachment to one of the FOXSI optical modules.

considers sitting one of these glued straight polycapillaries in front of one of the 10-shell optics. Since, according to the ray-trace simulation, singly reflected rays come from angles greater than 13 arcmin for this number of shells (see figure 2), a polycapillary with the dimensions described above and a length of 3.97 cm is needed. Due to the small dimensions, geometric consistency along the length of the polycapillaries, lightness, and on-axis open-area, the XOS optical device is an attractive solution for reducing singly reflected X-rays for the FOXSI rocket project and offers a potential technology to be explored and adapted to future satellite missions which use Wolter-I mirrors.

Opposed to the usual applications for the XOS polycapillaries that use each capillary as an optical fiber for X-rays, FOXSI requieres to reduce the internal reflections for every capilar to accomplish the goal of use the optical device as a singly reflected rays reducer for Wolter-I optics. Looking to explore the adaption of the internal roughness of the capillaries, FOXSI and XOS convened a NRE phase to explore three main points on the XOS side: i) Perform etching on sample bundles and confirm ability to eliminate reflections within the capillaries. ii) Design a process to bond many small bundles into the size needed to completely cover one of the FOXSI telescopes pupil. iii) Design a mount to hold the polycapillaries in front of a 10-shell FOXSI optics. The exploration phase will end by September 2017, and base on the results for each of the three items mentioned above, the FOXSI team will decide whether or not a set of polycapillaries will include for the third flight of the rocket.

Both, the FOXSI team at UC Berkeley, and XOS have worked together to design a mechanical interphase between the polycapillaries and one of the 10-shell optical modules. Details of such design are shown in figure 7. The mechanical design has been focused mainly on two aspects, the correct alignment of the polycapillaries with the FOXSI telescope, and the match of the dilatation thermal coefficient of the materials using to support both optical systems. The requirements are a co-alignment within one arcmin, and the use of 303 Stainless Steal to fabricate the XOS mounting that holds the polycapillaries, which is the material used to make the spiders that sustain the shells inside a FOXSI telescope. The whole optical system bundling the polycapillaries is likely to have a hexagonal shape, and the "corners" will be oversized compared to the spider.

3.2 Angular-slice blocker

Figure 8 shows that singly reflected X-rays come all together from the same region that can be angular limited with a rather high precision. This blocker would be ideal for observing faint regions (i.e. quiet sun) while a localized off-axis flare take place. Flight control on the roll angle of the payload is crucial in the implementation
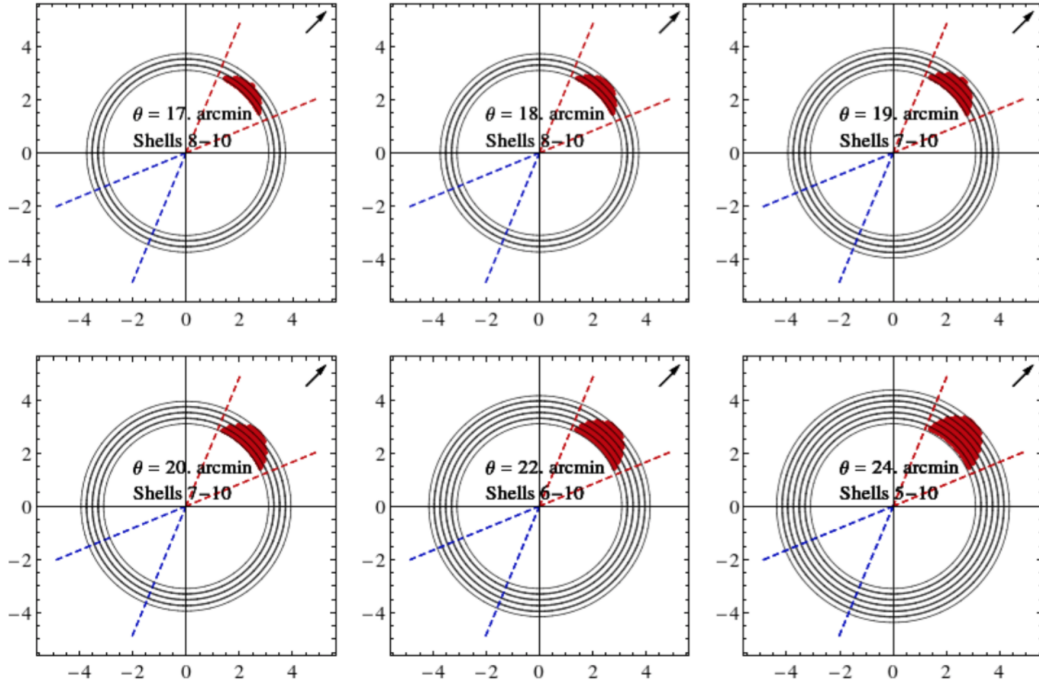
Figure 8. Pattern at the front of a 10-shell module of singly reflected X-rays which bounce only once on the hyperboloid mirrors.

of this design to block ghost rays. A big concern is the possibility of having two bright simultaneous off-axis sources at far away locations on the solar disk during the time of the rocket flight. Although this particular situation is unlikely since the Sun in entering in solar minimum; if presented during the observations, the angular slice blocker would be ineffective in stopping the ghost rays from all the sources.
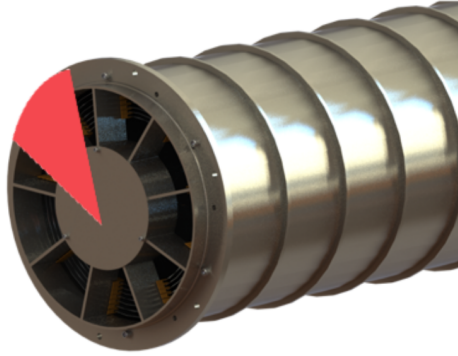

Figure 9. Angular blocker.

4. EFFECTIVENESS COMPARISONS

The key parameters for every option considered in this trade study to reduce singly reflected rays for a FOXSI telescope are summarized in table 1.

Parameter	Cylindrical baffles	Angular-slice blocker	Optical fibers for X-rays (polycapillaries)	Titanium 3D printed honeycomb collimator
Efficacy at reducing singly reflected rays	Long baffles (greater than 12 inches length) block most of the singly reflected rays	Depending on spacial configuration of the source(s) the efficacy range from ∼ 0% up to ∼ 100%	If internal reflectivity of fibers are minimized, the efficacy at reducing singly reflected rays can be close to ∼ 100%	Nominally close to 100%
Degradation of the total effective area	For thin baffles the effective area degradation is negligible	Degradation of the effective area is proportional to the area of the blocker	Degradation on-axis is proportional to the cross-section open area of the honeycomb structure	Degradation on-axis is proportional to the cross-section open area of the honeycomb structure
Space and weight limitations	The efficacy of this solution is proportional to the length of the baffles. However, there is limited room at the front of the FOXSI optics that cannot exceed 30 cm	The blocker is mechanically an easy solution to implement. It would weight less than a pound and would not protrude at the front of the telescopes	Current design is a cylinder full of polycapillaries, 3.97 cm long, 11.0 cm in diameter and 0.8 kg in mass.	Length = 19.5 cm, internal radius = 4.43 cm , external radius = 5.3 cm and a mass of 0.8 kg.
Fabrication constrains	New housing for modules is required. Co-alignment of the baffles with every shell is crucial for the correct functionality of the telescope	Should be made of a material dense enough to stop X-rays in the working energy range of FOXSI	Need to proof low (null) internal reflectivity of individual capillaries. Bundling process of several polycapillaries should preserve alignment. Thermal coefficient of the collimator mounting should match the one from the optics spider.	Make the smallest honeycomb structure by preserving the consistency of the geometry along the collimator. Need to satisfy environmental testing including vibration, thermal and outgassing.
Cost (USD)	$121k - $305k	$100	$45k	$ 25k
Calibration difficulties	A complete X-ray test is needed to confirm the straight radiation pattern is reduced.	Need to understand how a second bright source will affect the PSF in presence of the angular blocker.	A complete X-ray test is needed to confirm the straight radiation pattern is reduced.	A complete X-ray test is needed to confirm the straight radiation pattern is reduced.
Implications on pointing systems (LISS/MASS)	Serious implications. LISS and MASS would need to be relocated.	No implications.	Minor implications due to the small size of this collimator.	Minor implications unless want to include this kind of collimators at the front of every FOXSI module.
Mechanical implications	Serious implications. Due to the large length of the baffles, the mounting system for both the baffles and the optical modules would need to be design together.	It should be well attached to the FOXSI spider to keep in place during the flight.	Minor implications mostly due to the co-alignment of the collimator mounting with a FOXSI telescope, and the matching of thermal coefficients for those mountings.	Minor implications mostly due to the co-alignment of the collimator mounting with a FOXSI telescope.
Heritage to satellite missions	Not applicable for a satellite mission due the amount of space and weight this solution requieres.	Applicable with some modifications to allow angular mobility of the blocker.	If proof to reduce singly reflected rays for the rocket it may be a competitive option for a permanent satellite.	If pass environmental testing and the honeycomb structure is reduce in size it may become an option for a spacecraft.

Table 1. Trade study of four alternatives considered to reduce singly reflected rays for the FOXSI rocket experiment.

5. CONCLUSIONS

The mirrors location inside each of the FOXSI optical modules have large enough gaps between them to maximize the effective area of the instrument. The disadvantage of having such big gaps is the increase of contamination by single reflected rays. A dedicated X-ray component must then be added to reduce the amount of singly reflected rays that contrarily would substantially affect the sensitivity of the instrument for faint sources.

We have used ray-trace simulation results to asses the geometric structure of the singly reflected rays. Base on the simulation, we have come up with three ideas for optical devices to reduce the amount of singly reflected rays that can reach the FOXSI focal plane: i) Cylindrical baffles ii) Angular-slice blocker and iii) honeycomb collimator. The last one can be divided in two depending on the technology used for the honeycomb structure, i.e. X-ray optical fibers and titanium 64 3D printing.

After a trade study based on the information presented here, we have decided to consider the two honeycomb collimator options as plausible optical devices to reduce singly reflected rays for the third flight of the FOXSI rocket. They will be included in the rocket payload only if the fabrication constrain for each collimator is overcome.

ACKNOWLEDGMENTS

REFERENCES

[1] Krucker, S., Christe, S., Glesener, L., Ishikawa, S., Ramsey, B., Gubarev, M., Saito, S., Takahashi, T., Watanabe, S., Tajima, H., Tanaka, T., Turin, P., Glaser, D., Fermin, J., and Lin, R. P., "The focusing optics x-ray solar imager (FOXSI): instrument and first flight," in [*Solar Physics and Space Weather Instrumentation V*], **8862**, 88620R (Sept. 2013).

[2] Christe, S., Glesener, L., Buitrago-Casas, C., Ishikawa, S.-N., Ramsey, B., Gubarev, M., Kilaru, K., Kolodziejczak, J. J., Watanabe, S., Takahashi, T., Tajima, H., Turin, P., Shourt, V., Foster, N., and Krucker, S., "FOXSI-2: Upgrades of the Focusing Optics X-ray Solar Imager for its Second Flight," *Journal of Astronomical Instrumentation* **5**, 1640005–625 (Mar. 2016).

[3] Peterson, G. L. and Cote, M., "Lessons learned from the stray-light analysis of the xmm telescope," in [*Grazing Incidence and Multilayer X-Ray Optical Systems*], Hoover, R. B. and Walker, A. B. C., eds., *Proc. SPIE* **3113**, 321–333 (Jul. 1997). [doi:10.1117/12.278861].

[4] Cusumano, G., Artale, M. A., Mineo, T., Teresi, V., Pareschi, G., and Cotroneo, V., "Simbol-x: x-ray baffle for stray-light reduction," in [*Optics for EUV, X-Ray, and Gamma-Ray Astronomy III*], O'Dell, S. L. and Pareschi, G., eds., *Proc. SPIE* **6688**, 66880C (Sep. 2007). [doi:10.1117/12.732304].

[5] De Chambure, D., Lainé, R., Van Katwijk, K., and Kletzkine, P., "Xmm's x-ray telescopes," *ESA Bulletin* **100**, 30–42 (1999).

[6] Elsner, R. F., O'Dell, S. L., Ramsey, B. D., and Weisskopf, M. C., "Methods of optimizing x-ray optical prescriptions for wide-field applications," *arXiv preprint arXiv:1006.5065* (2010).